

Mucool - Linac facility- Heat exchanger sizing

cd 09/28/01 Fermilab

Goal

This program permits us to determine the size of the HX to be used for the mucool linac cooling chamber.

Volume reduction of 3" in the HX

Note- assumption:

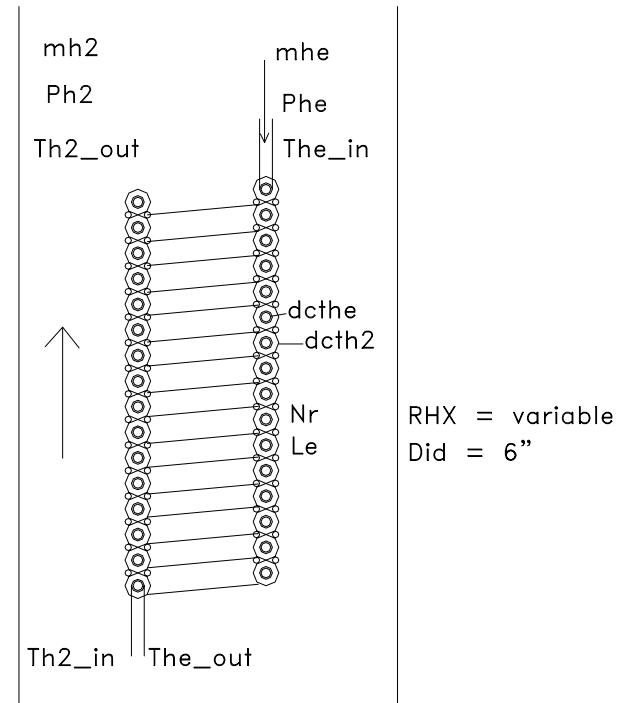
- Heat exchange: Helium/LH₂ co-current flow
- Number of iteration = 1000

Parameters

- Power to extract from the absorber Q=500 W
- Temperature in/out He loop T_{hein}=14 K T_{heout}=16.7 K
- Temperature in/out H₂ loop T_{h2in}=17.3 K T_{h2out}=17 K
- Pressure He/H₂ P_{he}=0.135 MPa P_{h2}=0.121 MPa
- Mass-flow He/H₂ m_{he}=35 g/s m_{h2}=210 g/s
- Helium properties (Hepak)

Schematic

- Inner diam. cooling tube = 0.555 inch
- Thickness = 0.035 inch



Results

1- Surface of the heat exchange

Surface_{HX}=0.185 m²

2- Length for dct=0.555 inch

L_e=4.177 m

3- If DHX=4.5 inch and dct =0.555 inch than

N_r = 12 spires and L_{e2}=4.331 m

4- Pressure drop in HX2

drop= 0.061psi

5- Pressure drop in He

drop= 3.478 psi

6- Heat transfer coeff.

h= 0.901 W/cm²*K

Comments: Fine for 500 W to remove at 17 K, with DT=0.3K, High DP he and DPh2

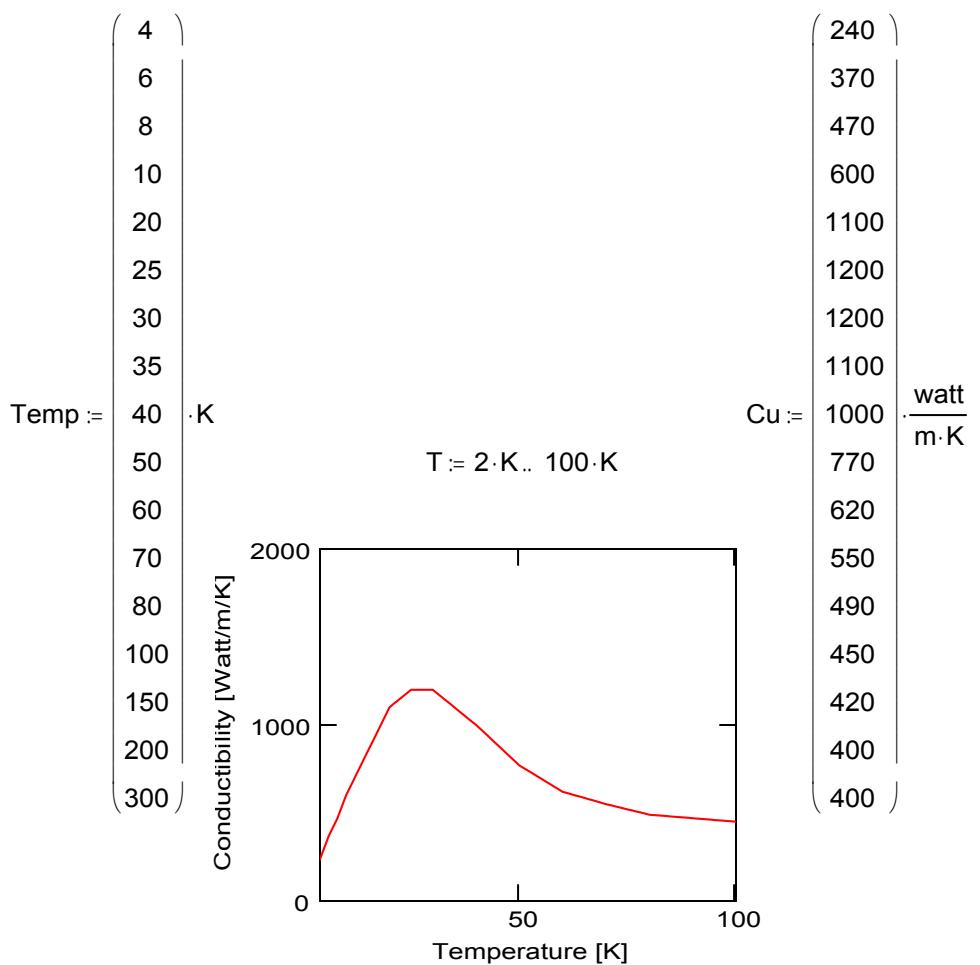
1. MATERIAL PROPERTIES

1.1.Thermal conductivity of copper

Data from file: CONDUC95.xls

Linear Interpolation

$$k_{Cu}(T) := \text{interp}(\text{Temp}, Cu, T)$$



1.2. Specific Heat of supercritical He at 1.35bar

Data from HEPAK

$$\text{Temp} := Y^{(1)} \cdot K$$

$$cp_{He} := Y^{(5)} \cdot \frac{\text{joule}}{\text{kg} \cdot \text{K}}$$

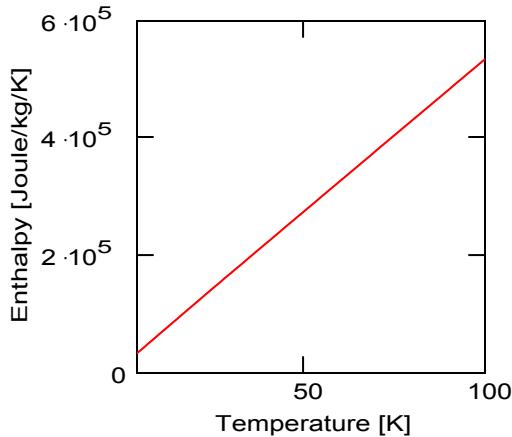
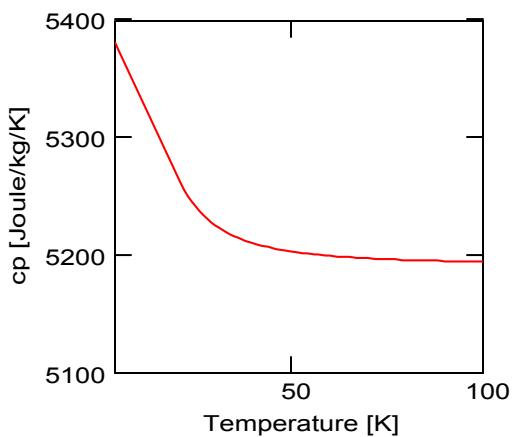
$$cp_{He}(T) := \text{interp}(\text{Temp}, cp_{He}, T)$$

$$cp_{He}(4 \cdot K) = 5.381 \times 10^3 \text{ kg}^{-1} \text{ K}^{-1} \text{ joule}$$

$$Y := \text{READPRN}("He1_35bar.prn")$$

$$H_{He} := Y^{(6)} \cdot \frac{\text{joule}}{\text{kg}}$$

$$H_{He}(T) := \text{interp}(\text{Temp}, H_{He}, T)$$



$T := 0 \text{..} 300 \text{K}$

density	viscosity	conductivity	specific heat	enthalphy
$\rho_{\text{He}} := Y^{(2)} \cdot \frac{\text{kg}}{\text{m}^3}$	$\mu_{\text{He}} := Y^{(3)} \cdot \text{Pa} \cdot \text{sec}$	$k_{\text{He}} := Y^{(4)} \cdot \frac{\text{watt}}{\text{m} \cdot \text{K}}$	$c_{\text{pHe}} := Y^{(5)} \cdot \frac{\text{joule}}{\text{kg} \cdot \text{K}}$	$H_{\text{He}} := Y^{(6)} \cdot \frac{\text{joule}}{\text{kg}}$
$\rho_{\text{He}}(T) := \text{interp}(\text{Temp}, \rho_{\text{He}}, T)$			$\rho_{\text{He}}(65 \text{K}) = 0.997 \text{ kg m}^{-3}$	
$\mu_{\text{He}}(T) := \text{interp}(\text{Temp}, \mu_{\text{He}}, T)$			$\mu_{\text{He}}(65 \text{K}) = 7.482 \times 10^{-6} \text{ kg m}^{-1} \text{ sec}^{-1}$	
$k_{\text{He}}(T) := \text{interp}(\text{Temp}, k_{\text{He}}, T)$			$k_{\text{He}}(65 \text{K}) = 0.055 \text{ m}^{-1} \text{ K}^{-1} \text{ watt}$	
$c_{\text{pHe}}(T) := \text{interp}(\text{Temp}, c_{\text{pHe}}, T)$			$c_{\text{pHe}}(65 \text{K}) = 5.199 \times 10^3 \text{ kg}^{-1} \text{ K}^{-1} \text{ joule}$	
$H_{\text{He}}(T) := \text{interp}(\text{Temp}, H_{\text{He}}, T)$			$H_{\text{He}}(19.477 \text{K}) = 1.156 \times 10^5 \text{ kg}^{-1} \text{ joule}$	

1.3. Specific Heat of supercritical Hydrogen at 1.21bar

Data from GASPAK

$Y_{\text{H2}} := \text{READPRN("H2_1bar21.prn")}$

$$\text{Temp} := Y_{\text{H2}}^{(1)} \cdot \text{K}$$

$$c_{\text{pH2}} := Y_{\text{H2}}^{(5)} \cdot \frac{\text{joule}}{\text{kg} \cdot \text{K}}$$

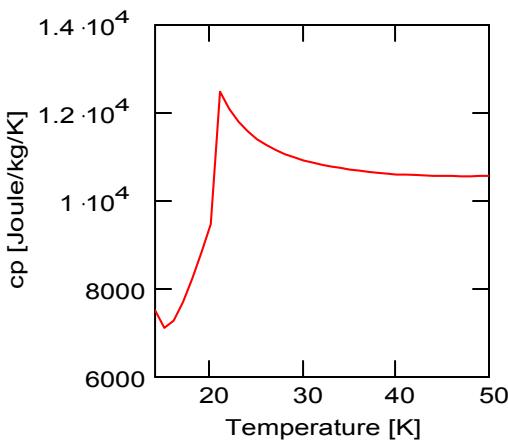
$$c_{\text{pH2}}(T) := \text{interp}(\text{Temp}, c_{\text{pH2}}, T)$$

$$c_{\text{pH2}}(14 \text{K}) = 7.516 \times 10^3 \text{ kg}^{-1} \text{ K}^{-1} \text{ joule}$$

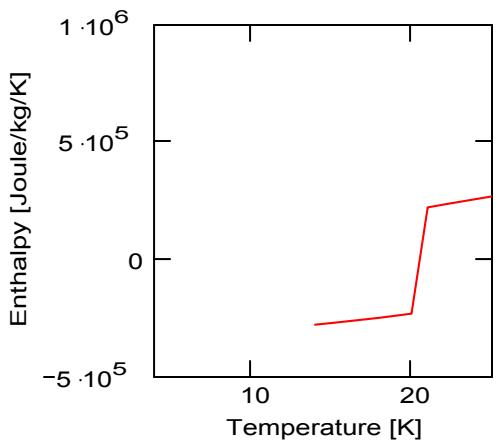
$$T := 14 \text{..} 50$$

$$H_{\text{H2}} := Y_{\text{H2}}^{(6)} \cdot \frac{\text{joule}}{\text{kg}}$$

$$H_{\text{H2}}(T) := \text{interp}(\text{Temp}, H_{\text{H2}}, T)$$



$$T := 0 \text{..} 300 \text{K}$$



density	viscosity	conductivity	specific heat	enthalphy
$\rho_{\text{H2}} := Y_{\text{H2}}^{(2)} \cdot \frac{\text{kg}}{\text{m}^3}$	$\mu_{\text{H2}} := Y_{\text{H2}}^{(3)} \cdot \text{Pa} \cdot \text{sec}$	$k_{\text{H2}} := Y_{\text{H2}}^{(4)} \cdot \frac{\text{watt}}{\text{m} \cdot \text{K}}$	$c_{\text{pH2}} := Y_{\text{H2}}^{(5)} \cdot \frac{\text{joule}}{\text{kg} \cdot \text{K}}$	$H_{\text{H2}} := Y_{\text{H2}}^{(6)} \cdot \frac{\text{joule}}{\text{kg}}$
$\rho_{\text{H2}}(T) := \text{interp}(\text{Temp}, \rho_{\text{H2}}, T)$			$\rho_{\text{H2}}(65 \text{K}) = 0.41 \text{ kg m}^{-3}$	
$\mu_{\text{H2}}(T) := \text{interp}(\text{Temp}, \mu_{\text{H2}}, T)$			$\mu_{\text{H2}}(65 \text{K}) = 3.054 \times 10^{-6} \text{ kg m}^{-1} \text{ sec}^{-1}$	
$k_{\text{H2}}(T) := \text{interp}(\text{Temp}, k_{\text{H2}}, T)$			$k_{\text{H2}}(65 \text{K}) = 0.047 \text{ kg m sec}^{-3} \text{ K}^{-1}$	
$c_{\text{pH2}}(T) := \text{interp}(\text{Temp}, c_{\text{pH2}}, T)$			$c_{\text{pH2}}(65 \text{K}) = 1.057 \times 10^4 \text{ m}^2 \text{ sec}^{-2} \text{ K}^{-1}$	
$H_{\text{H2}}(T) := \text{interp}(\text{Temp}, H_{\text{H2}}, T)$			$H_{\text{H2}}(65 \text{K}) = 6.973 \times 10^5 \text{ kg}^{-1} \text{ joule}$	

2. DATA - input

$$Q := 500 \cdot \text{watt}$$

$$i_{\max} := 1000$$

$$m_{dotHe} := 35 \cdot 10^{-3} \cdot \frac{\text{kg}}{\text{sec}}$$

$$m_{dotH2} := 210 \cdot 10^{-3} \cdot \frac{\text{kg}}{\text{sec}}$$

2.1. choose a set of temperatures:

$$T_{in} := 14 \cdot \text{K}$$

$$T_{2in} := 17.3 \cdot \text{K}$$

$$T_{out} := 16.7 \cdot \text{K}$$

$$T_{2out} := 17 \cdot \text{K}$$

2.2. Geometry

a) HX lenght - Solution 1

$$Nr := 12$$

Number of spires

$$DHX := 4.5 \cdot \text{in}$$

$$RHX := \frac{DHX}{2}$$

$$Le := 2 \cdot \pi \cdot RHX \cdot Nr \quad Le = 4.309 \text{ m}$$

Solution 2

$$Nr2 := 12$$

Number of spires

$$DHX2 := 4.5 \cdot \text{in}$$

$$RHX2 := \frac{DHX2}{2}$$

$$Le2 := 2 \cdot \pi \cdot RHX2 \cdot Nr2 \quad Le2 = 4.309 \text{ m}$$

c) Hx cooling spire

$$dcthe := 0.555 \cdot 25.4 \cdot \text{mm}$$

cooling tube inner diameter

$$dcthe = 14.097 \text{ mm}$$

$$thct := 0.035 \cdot 25.4 \cdot \text{mm}$$

wall thickness of cooling tube -

Any thickness would fit
if Q_c is very large..

$$thct = 0.889 \text{ mm}$$

$$dcth2 := dcthe + 2 \cdot thct$$

cooling tube outer diameter

$$dctheout := dcth2$$

d) HX - outer shell

$$Did := 6 \cdot \text{in}$$

$$Dred := 3 \cdot \text{in}$$

$$AH2 := 3.14 \cdot \frac{\left[\left(Did - 2 \cdot \frac{5 \cdot \text{in}}{8} \right)^2 - Dred^2 \right]}{4} \quad AH2 = 6.869 \times 10^{-3} \text{ m}^2$$

$$Per := 3.14 \cdot (Did + Dred)$$

$$DHXh := 4 \cdot \frac{AH2}{Per} \quad \text{Hydraulic diameter: } DHXh = 0.038 \text{ m}$$

$$LHX := 20 \cdot \text{in}$$

$$Acthe := \pi \cdot \left(\frac{dcthe}{2} \right)^2$$

cross-section area He

$$Acthe = 1.561 \times 10^{-4} \text{ m}^2$$

$$Ah2 := \pi \cdot \left(\frac{DHXh}{2} \right)^2$$

cross-section area H2

$$Ah2 = 1.151 \times 10^{-3} \text{ m}^2$$

Determine the lenght of the HX for Nr spires

$$Scthe := \pi \cdot dcthe \cdot Le \quad \text{inner surface area cooling tube}$$

$$Scth2 := \pi \cdot dcth2 \cdot Le \quad \text{outer surface area cooling tube}$$

$$Lhx := Nr \cdot dcth2$$

$$Lhx = 7.5 \text{ in}$$

$$Scthe = 0.191 \text{ m}^2$$

$$Scth2 = 0.215 \text{ m}^2$$

3. COOLING SCHEME:

3.1. Forced convection heat transfer coefficients (turbulent flow)

$$\text{Pr}(\mu, \text{cp}, k, T) := \mu(T) \cdot \frac{\text{cp}(T)}{k(T)}$$

Prandtl number

$$\text{Re}(\rho, v, d, \mu, T) := \rho(T) \cdot v \cdot \frac{d}{\mu(T)}$$

Reynolds number

$$\text{Nuh2}(\text{Re}) := 0.083 \cdot \text{Re}^{0.85}$$

Nusselt number - hydrogen - shell side

$$\text{Nu}(\text{Re}, \text{Pr}) := 0.023 \cdot \text{Re}^{0.8} \cdot \text{Pr}^{0.4}$$

Nusselt number - helium -inner side

$$h(\text{Nu}, k, T, d) := \text{Nu} \cdot \frac{k(T)}{d}$$

convection heat transfer coefficient
for natural convection in monophasic He

3.2. Helium flow velocities

$$\text{mdothe} = 0.035 \text{ kg sec}^{-1}$$

He mass flow rate

$$v_{\text{He}_i} := \frac{\text{mdothe}}{\text{Acthe} \cdot \rho_{\text{He}}(\text{The}_i)}$$

v_{He_i}

$$\text{Pr}_{\text{He}_i} := \text{Pr}(\mu_{\text{He}}, \text{cp}_{\text{He}}, k_{\text{He}}, \text{The}_i)$$

Pr_{He}

$$\text{Re}_{\text{He}_i} := \text{Re}(\rho_{\text{He}}, v_{\text{He}_i}, \text{dcthe}, \mu_{\text{He}}, \text{The}_i)$$

Re_{He}

$$\text{Nu}_{\text{He}_i} := \text{Nu}(\text{Re}_{\text{He}_i}, \text{Pr}_{\text{He}_i})$$

Nu_{He}

$$h_{\text{cthe}_i} := h(\text{Nu}_{\text{He}_i}, k_{\text{He}}, \text{The}_i, \text{dcthe})$$

h_{cthe}

$i := 1 .. \text{imax}$

$$\text{The}_i := \text{Thein} + i \cdot \frac{(\text{Theout} - \text{Thein})}{\text{imax}}$$

$$\text{mdothe} = 0.035 \text{ kg sec}^{-1}$$

$$\text{Acthe} = 1.561 \times 10^{-4} \text{ m}^2$$

$$\text{Pr}_{\text{He}1000} = 0.722$$

$$\text{Re}_{\text{He}1000} = 9.795 \times 10^5$$

$$\text{Acthe} = 1.561 \times 10^{-4} \text{ m}^2$$

$$\text{The}_{1000} = 16.7 \text{ K}$$

$$\text{dcthe} = 0.014 \text{ m}$$

$$v_{\text{He}1000} = 59.943 \text{ m sec}^{-1}$$

3.3. Hydrogen flow velocities

$$\text{mdoth2} = 0.21 \text{ kg sec}^{-1}$$

Hydrogen mass flow rate

$$v_{\text{H2}}(m, A, \rho, T) := \frac{m}{A \cdot \rho(T)}$$

$$v_{\text{H2}_i} := v_{\text{H2}}(\text{mdoth2}, \text{Ah2}, \rho_{\text{H2}}, \text{Th2}_i)$$

v_{H2}

$$\text{Pr}_{\text{H2}_i} := \text{Pr}(\mu_{\text{H2}}, \text{cp}_{\text{H2}}, k_{\text{H2}}, \text{Th2}_i)$$

Pr_{H2}

$$\text{Re}_{\text{H2}_i} := \text{Re}(\rho_{\text{H2}}, v_{\text{H2}_i}, \text{dch2}, \mu_{\text{H2}}, \text{Th2}_i)$$

Re_{H2}

$$\text{Nuh2}_i := \text{Nuh2}(\text{Re}_{\text{H2}_i})$$

Nuh2

$$h_{\text{cth2}_i} := h(\text{Nuh2}_i, k_{\text{H2}}, \text{Th2}_i, \text{dch2})$$

h_{cth2}

$$\text{Th2}_i := \text{Th2out} - \left[i \cdot \frac{(\text{Th2out} - \text{Th2in})}{\text{imax}} \right]$$

$$\text{mdoth2} = 0.21 \text{ kg sec}^{-1}$$

$$\text{Ah2} = 1.151 \times 10^{-3} \text{ m}^2$$

$$\text{Re}_{\text{H2}1000} = 1.626 \times 10^5$$

3.4. Calculation of the wall temperature

$$T_{cti} := \frac{[(The_i \cdot hcthe_i) + (Th2_i \cdot hcth2_i)]}{(hcthe_i + hcth2_i)}$$

The_i Th2_i T_{cti}

3.5. Convection in helium

$$Scthe_i := \frac{\frac{Q}{imax}}{hcthe_i \cdot (T_{cti} - The_i)}$$

Scthe_i

3.6. Convection in hydrogen

$$Scth2_i := \frac{\frac{Q}{imax}}{(-hcth2)_i \cdot (T_{cti} - Th2_i)}$$

Scth2_i

3.7. Calculation of the HX surface and lenght

$$SurfaceHX := \sum_i Scth2_i$$

$$dcthe = 0.014 \text{ m}$$

$$L(d) := \frac{SurfaceHX}{\pi \cdot d}$$

Surface of exchange

$$SurfaceHX = 0.185 \text{ m}^2$$

Lenght of HX for dcthe

$$L(dcthe) = 4.1774 \text{ m}$$

4. Approach with the flux balance

4.1. Solid conduction

$$thct = 8.89 \times 10^{-4} \text{ m}$$

$$Le = 4.309 \text{ m}$$

$$Scthe := \pi \cdot dcthe \cdot Le$$

$$Scthe = 0.191 \text{ m}^2$$

$$Scth2 := \pi \cdot dthct \cdot Le$$

$$Scth2 = 0.215 \text{ m}^2$$

$$Qs(Tcth2) := \frac{Scthe}{thct \cdot Le} \cdot \int_{Tcthe}^{Tcth2} kCu(T) dT$$

$$Tcthe := 16.6 \text{ K}$$

$$Tcth2 := 17.45 \text{ K}$$

used for Qs calculation

$$Le2 = 4.309 \text{ m}$$

$$The := \frac{Thein + Theout}{2}$$

$$The = 15.35 \text{ K}$$

$$Th2 := \frac{Th2in + Th2out}{2}$$

$$Th2 = 17.15 \text{ K}$$

heat conduction path though the wall thickness

$$Qs(Tcth2) = 4.028 \times 10^4 \text{ m}^{-1} \text{ watt}$$

4.2. Power to extract from the hydrogen

$$Ptot := \frac{Q}{Le2}$$

$$Ptot = 116.036 \text{ m}^{-1} \text{ watt}$$

4.3. Helium Cooling Capacity

$$pHe(mdothe, Theout, Thein) := \frac{[mdothe \cdot cpHe(The) \cdot (Theout - Thein)]}{Le2}$$

pHe(mdothe, Theout, Thein) = 116.278 m⁻¹ watt

4.4. Hydrogen Cooling Capacity

$$\rho H_2(m_{\text{d}} \cdot T_{\text{out}}, T_{\text{in}}) := \frac{-(m_{\text{d}} \cdot (H_2(T_{\text{out}}) - H_2(T_{\text{in}})))}{L_e}$$

$$\rho H_2(m_{\text{d}} \cdot T_{\text{out}}, T_{\text{in}}) = 114.04 \text{ m}^{-1} \text{ watt}$$

4.5. Convection in helium

$$\rho He := \rho He(T_{\text{c}}) \quad \rho He = 3.756 \text{ kg m}^{-3} \quad d_{\text{c}} = 0.014 \text{ m}$$

$$\mu He := \mu He(T_{\text{c}}) \quad \mu He = 3.216 \times 10^{-6} \text{ sec}^2 \text{ m}^{-3} \text{ watt} \quad T_{\text{c}} = 16.6 \text{ K}$$

$$v_{\text{He}} := \frac{m_{\text{d}} \cdot v_{\text{He}}}{A_{\text{c}} \cdot \rho_{\text{He}}} \quad v_{\text{He}} = 59.703 \text{ m sec}^{-1}$$

$$c_{\text{p}} He := c_{\text{p}} He(T_{\text{c}}) \quad c_{\text{p}} He = 5.293 \times 10^3 \text{ m}^2 \text{ sec}^{-2} \text{ K}^{-1}$$

$$k_{\text{He}} := k_{\text{He}}(T_{\text{c}}) \quad k_{\text{He}} = 0.024 \text{ kg m sec}^{-3} \text{ K}^{-1}$$

$$Re_{\text{He}}(\rho, v, d, \mu) := \rho \cdot v \cdot \frac{d}{\mu} \quad Re_{\text{He}} := Re_{\text{He}}(\rho_{\text{He}}, v_{\text{He}}, d_{\text{c}}, \mu_{\text{He}}) \quad Re_{\text{He}} = 9.829 \times 10^5$$

$$Pr_{\text{He}}(\mu, c_{\text{p}}, k) := \mu \cdot \frac{c_{\text{p}}}{k} \quad Pr_{\text{He}} := Pr_{\text{He}}(\mu_{\text{He}}, c_{\text{p}}_{\text{He}}, k_{\text{He}}) \quad Pr_{\text{He}} = 0.722$$

$$Nu(Re, Pr) := 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \quad Nu_{\text{He}} := Nu(Re_{\text{He}}, Pr_{\text{He}}) \quad Nu_{\text{He}} = 1.256 \times 10^3$$

$$h(Nu, k, d) := Nu \cdot \frac{k}{d} \quad h_{\text{c}} := h(Nu_{\text{He}}, k_{\text{He}}, d_{\text{c}}) \quad h_{\text{c}} = 2.102 \times 10^3 \text{ m}^{-2} \text{ K}^{-1} \text{ watt}$$

$$Q_c(The, T_{\text{c}}) := \frac{S_{\text{c}} \cdot h_{\text{c}} \cdot (T_{\text{c}} - The)}{L_e} \quad Q_c(The, T_{\text{c}}) = 116.372 \text{ m}^{-1} \text{ watt}$$

$$T_{\text{c}} = 16.6 \text{ K}$$

4.6. Convection in hydrogen

$$\rho H_2 := \rho H_2(T_{\text{c}}) \quad \rho H_2 = 73.848 \text{ kg m}^{-3} \quad d_{\text{c}} = 0.016 \text{ m}$$

$$\mu H_2 := \mu H_2(T_{\text{c}}) \quad \mu H_2 = 1.757 \times 10^{-5} \text{ sec}^2 \text{ m}^{-3} \text{ watt} \quad T_{\text{c}} = 17.45 \text{ K}$$

$$v H_2 := \frac{m_{\text{d}} \cdot v}{A_{\text{c}} \cdot \rho H_2} \quad v H_2 = 2.471 \text{ m sec}^{-1}$$

$$c_{\text{p}} H_2 := c_{\text{p}} H_2(T_{\text{c}}) \quad c_{\text{p}} H_2 = 7.928 \times 10^3 \text{ m}^2 \text{ sec}^{-2} \text{ K}^{-1}$$

$$k H_2 := k H_2(T_{\text{c}}) \quad k H_2 = 0.099 \text{ kg m sec}^{-3} \text{ K}^{-1}$$

$$Re_{\text{H}_2}(\rho, v, d, \mu) := \rho \cdot v \cdot \frac{d}{\mu} \quad Re_{\text{H}_2} := Re_{\text{H}_2}(\rho_{\text{H}_2}, v_{\text{H}_2}, d_{\text{c}}, \mu_{\text{H}_2}) \quad Re_{\text{H}_2} = 1.649 \times 10^5$$

$$Pr_{\text{H}_2}(\mu, c_{\text{p}}, k) := \mu \cdot \frac{c_{\text{p}}}{k} \quad Pr_{\text{H}_2} := Pr_{\text{H}_2}(\mu_{\text{H}_2}, c_{\text{p}}_{\text{H}_2}, k_{\text{H}_2}) \quad Pr_{\text{H}_2} = 1.402$$

$$Nuh_2(Re) := 0.083 \cdot Re^{0.85} \quad Nuh_2 := Nuh_2(Re_{\text{H}_2}) \quad Nuh_2 = 2.258 \times 10^3$$

$$h(Nu, k, d) := Nu \cdot \frac{k}{d} \quad h_{\text{c}} := h(Nuh_2, k_{\text{H}_2}, d_{\text{c}}) \quad h_{\text{c}} = 1.413 \times 10^4 \text{ m}^{-2} \text{ K}^{-1} \text{ watt}$$

$$Q_{\text{ch}}(Th_2, T_{\text{c}}) := \frac{S_{\text{c}} \cdot h_{\text{c}} \cdot (T_{\text{c}} - Th_2)}{L_e} \quad Q_{\text{ch}}(Th_2, T_{\text{c}}) = 211.416 \text{ m}^{-1} \text{ watt}$$

$$T_{\text{c}} = 17.45 \text{ K}$$

4.7. Pressure drop In helium circuit

$$f_{he} := 0.00332 + \frac{0.221}{Re_{he}^{0.237}}$$

$$\text{drop} := f_{he} \cdot \frac{Le \cdot \rho_{He} \cdot v_{He}^2}{dc_{the} \cdot 2}$$

$$\text{drop2} := f_{he} \cdot \frac{Le_2 \cdot \rho_{He} \cdot v_{He}^2}{dc_{the} \cdot 2}$$

$$Re_{he} = 9.829 \times 10^5$$

$$f := 0.003$$

turbulent

$$dc_{the} = 0.014 \text{ m}$$

The

$$f_{he} = 0.012$$

$$\rho_{He} = 3.756 \text{ kg m}^{-3}$$

$$v_{He} = 59.703 \text{ m sec}^{-1}$$

$$Le_2 = 4.309 \text{ m}$$

$$DHx_h = 0.038 \text{ m}$$

$$\text{drop} = 2.398 \times 10^4 \text{ Pa}$$

$$\text{drop} = 3.478 \text{ psi}$$

$$\text{drop2} = 2.398 \times 10^4 \text{ Pa}$$

$$\text{drop2} = 3.478 \text{ psi}$$

In Hydrogen circuit

$$f_{h2} := \frac{1}{(1.8 \cdot \log(Re_{h2}) - 1.64)^2}$$

$$f_{h2} = 0.017$$

$$Re_{h2} = 1.649 \times 10^5$$

$$\rho_{H2} = 73.848 \text{ kg m}^{-3}$$

$$v_{H2} = 2.471 \text{ m sec}^{-1}$$

$$\text{drop}_{h2} = 422.576 \text{ Pa}$$

$$\text{drop}_{h2} = 0.061 \text{ psi}$$

$$Le_2 = 4.309 \text{ m}$$

$$DHx_h = 0.038 \text{ m}$$

4.8. RESULTS

$$Q_c(\text{The}, T_{c_{the}}) = 116.372 \text{ m}^{-1} \text{ watt}$$

$$Q = 500 \text{ watt}$$

$$P_{tot} = 116.036 \text{ m}^{-1} \text{ watt}$$

The Q_s is larger than Q_i - any thickness of the copper cooling tube would fit - this parameter is not a limitation

$$Q_s(T_{c_{th2}}) = 4.028 \times 10^4 \text{ m}^{-1} \text{ watt}$$

$$Q_{ch2}(T_{h2}, T_{c_{th2}}) = 211.416 \text{ m}^{-1} \text{ watt}$$

$$Q_s(T)$$

$$Q_c(\text{The}, T)$$

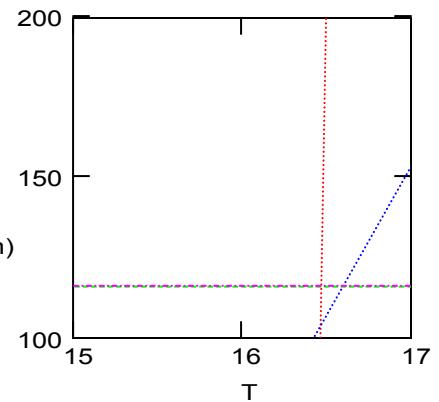
$$P_{tot}$$

$$p_{He}(m_{d0} \text{the}, T_{out}, T_{in})$$

$$p_{He}(m_{d0} \text{the}, T_{out}, T_{in}) = 116.278 \text{ m}^{-1} \text{ watt}$$

$$p_{H2}(m_{d0} \text{th2}, T_{out}, T_{in}) = 114.04 \text{ m}^{-1} \text{ watt}$$

$$T := 4 \cdot K.. 200 \cdot K$$



SUMMARY

$$Q = 500 \text{ watt}$$

$$P_{\text{tot}} = 116.036 \text{ m}^{-1} \text{ watt}$$

$$\text{SurfaceHX} = 0.185 \text{ m}^2$$

$$L(\text{dcthe}) = 4.177 \text{ m}$$

Helium

$$T_{\text{hein}} = 14 \text{ K}$$

$$T_{\text{he}} = 15.35 \text{ K}$$

$$S_{\text{cthe}} = 0.191 \text{ m}^2$$

$$m_{\text{dothe}} = 0.035 \text{ kg sec}^{-1}$$

$$T_{\text{heout}} = 16.7 \text{ K}$$

$$m_{\text{dothe}} = 0.035 \text{ kg sec}^{-1}$$

$$\text{drop} = 2.398 \times 10^4 \text{ Pa}$$

$$\text{drop} = 3.478 \text{ psi}$$

$$\text{drop2} = 2.398 \times 10^4 \text{ Pa}$$

$$\text{drop2} = 3.478 \text{ psi}$$

Hydrogen

$$T_{\text{h2in}} = 17.3 \text{ K}$$

$$T_{\text{h2}} = 17.15 \text{ K}$$

$$S_{\text{cth2}} = 0.215 \text{ m}^2$$

$$m_{\text{doth2}} = 0.21 \text{ kg sec}^{-1}$$

$$T_{\text{h2out}} = 17 \text{ K}$$

$$\text{drop}_{\text{h2}} = 422.576 \text{ Pa}$$

$$\text{drop}_{\text{h2}} = 0.061 \text{ psi}$$

$$m_{\text{doth2}} = 0.21 \text{ kg sec}^{-1}$$

Proposal for the HX design, Nr number of spire, RHX, radius

$$DHX = 4.5 \text{ in}$$

$$Nr = 12$$

$$RHX = 0.057 \text{ m}$$

$$Le = 4.309 \text{ m}$$

$$\text{drop} = 3.478 \text{ psi}$$

$$DHX2 = 4.5 \text{ in}$$

$$Nr2 = 12$$

$$RHX2 = 0.057 \text{ m}$$

$$Le2 = 4.309 \text{ m}$$

$$\text{drop2} = 3.478 \text{ psi}$$

$$i_{\max} = 1 \times 10^3$$

Compare to: $L(\text{dcthe}) = 4.177 \text{ m}$

$$dc_{\text{the}} = 14.097 \text{ mm}$$

$$dc_{\text{theout}} = 0.016 \text{ m}$$

$$th_{\text{ct}} = 8.89 \times 10^{-4} \text{ m}$$

Heat transfer coefficient

$$h := \frac{Q}{\text{SurfaceHX} \cdot (T_{\text{h2in}} - T_{\text{h2out}})}$$

$$h = 0.901 \text{ K}^{-1} \frac{\text{watt}}{\text{cm}^2}$$

$$(T_{\text{h2in}} - T_{\text{h2out}}) = 0.3 \text{ K}$$

$$\text{SurfaceHX} = 0.185 \text{ m}^2$$

$$Q = 500 \text{ watt}$$

